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Are the Pyrenees a barrier for the transport of birch (*Betula*) pollen from Central Europe to the Iberian Peninsula?

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ABSTRACT

This work provides a first assessment of the possible barrier effect of the Pyrenees on the atmospheric transport of airborne pollen from Europe to the North of the Iberian Peninsula. Aerobiological data recorded in three Spanish stations located at the eastern, central and western base of the Pyrenees in the period 2004–2014 have been used to identify the possible long range transport episodes of *Betula* pollen. The atmospheric transport routes and the origin regions have been established by means of trajectory analysis and a source receptor model. *Betula* pollen outbreaks were associated with the meteorological scenario characterized by the presence of a high-pressure system over Southern British Islands reinforced by a low-pressure system over Morocco and Southern Iberian Peninsula. France and Central Europe have been identified as the probable source areas of *Betula* pollen that arrives to Northern Spain. However, the specific source areas are mainly determined by the particular prevailing atmospheric circulation of each location. Finally, the Weather Research and Forecasting model highlighted the effect of the orography on the atmospheric transport patterns, showing paths through the western and easternmost lowlands for Vitoria-Gasteiz and Bellaterra respectively, and the direct impact of air flows over Vielha through the Garona valley.

1. Introduction

Pollination is a biologically-relevant process that affects the structure of ecosystems, since pollen is responsible for gene flow (Ellstrand, 1992; Ennos, 1994; Burczyk et al., 2004; Belmonte et al., 2008), and it contributes to determine the spatial distribution of plant species (Ellstrand, 1992; Smouse et al., 2001; Sharma and Khanduri, 2007; Schmidt-Lebuhn et al., 2007; Belmonte et al., 2008). On the other hand, airborne pollen released into the atmosphere by anemophilous plants can induce allergic symptoms in the atopic population, and also increase the sensitization of the overall population (D'Amato et al., 2007). Currently, it is widely accepted that pollen released to the atmosphere can be transported large distances under favourable meteorological conditions (Sofiev et al., 2012). Therefore, airborne pollen transport is becoming increasingly important due to its implications in terms of biogeography and public health.

It is well known that the orography of the European mountain systems has been a strong influence on the biogeography and evolution of mountain and high latitude species (Schmitt, 2009; Karrer et al., 2015). The Pyrenean chain is a major mountain range in SW Europe. Due to its elevation (up to 3400 m) and its spatial extent (> 400 km) this chain is an altitudinal obstacle between the Iberian Peninsula and the rest of Europe that has strongly affected the distribution and genetic structures of native species (Haran et al., 2015). However, are the Pyrenees a real barrier for the atmospheric transport of pollen between Europe and Iberian Peninsula?

In this context, birch (*Betula* sp. hereafter *Betula*) pollen has been selected to study the long range transport of pollen across the Pyrenees. On the one hand, *Betula* trees produce large amounts of highly allergenic pollen, particularly it has been estimated that on average each inflorescence produces 10,044,000 pollen grains (Piotrowska, 2008), ranging from 1000 to 10,000 pollen grains/m^3 the daily average of airborne *Betula* pollen concentrations observed during the peak birch pollen season in Northern Europe (Ranta et al., 2008). *Betula* pollen is distributed by wind and impacts human health by causing seasonal hay fever, pollen-related asthma, and other allergic diseases (Müller-Germann et al., 2015), being one of the most important causes of respiratory allergy in Northern and Central Europe (Emberlin et al., 1993, 1997; Spieksma et al., 1995; Heinzerling et al., 2009). On the other hand, *Betula* trees are abundant in Central, Northern and Eastern Europe, but are scarce in the Mediterranean territories, especially in Spain, of which northern regions constitutes a southern border of the distribution area (De Bolòs et al., 1990). *Betula pubescens* has a more northerly and easterly distribution, whereas *Betula pendula* can reach southern regions such as Iberian Peninsula, South Italy and Greece (Beck et al., 2016; Fig. 1). Airborne *Betula* pollen is present in Spain from March to the end of

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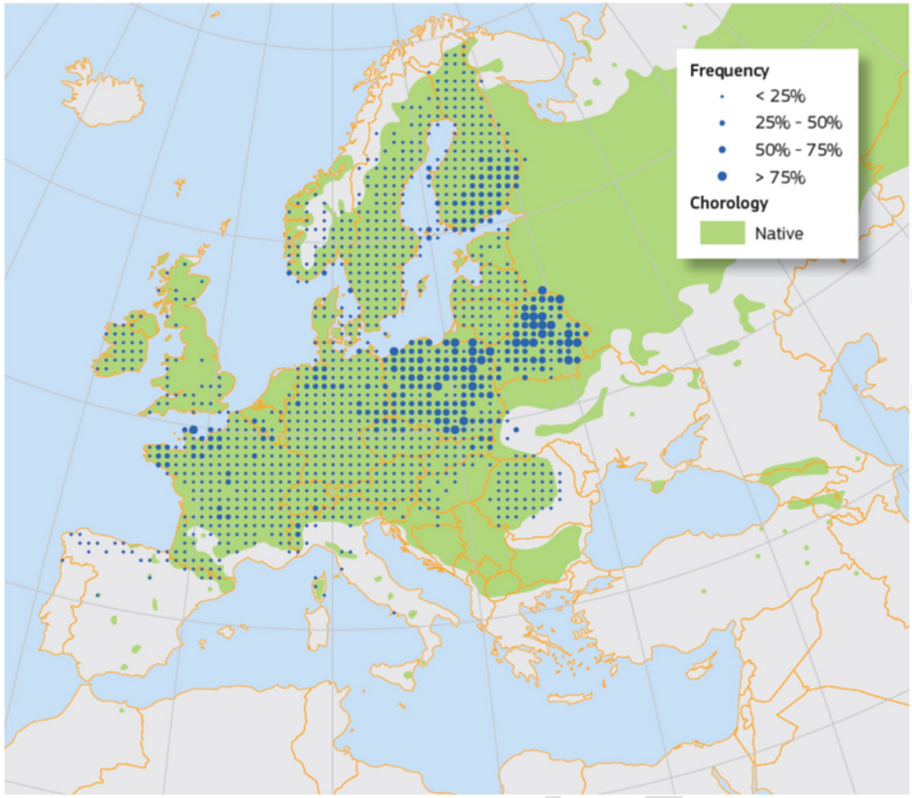

Fig. 1. Plot distribution and simplified chorology map for *Betula pendula*. Frequency of *B. pendula* occurrences within the field observations as reported by the National Forest Inventories (Beck et al., 2016).

May, and it only reaches high concentration in the N, being the highest concentrations recorded in the NW corner of the Iberian Peninsula (Jato et al., 1999). Nevertheless, punctual peaks are observed in other N Iberian Peninsula zones due to the long-range transport (LRT thereafter) under particular meteorological circumstances (Sofiev et al., 2015). This is especially important in Catalonia (NE Spain), where allergy to *Betula* pollen is not very frequent (Pereira et al., 2006), but it occurs and the intensity of derived health problems can be increased by LRT pollen episodes. These potential allergenic diseases outbreaks have been previously registered for other allergenic pollen types in Catalonia, such **as** *Ambrosia* (Belmonte et al., 2000; Fernández-Llamazares et al., 2014) and *Fagus* (Belmonte et al., 2008). Conversely, *Betula* pollen is a common cause of pollinosis in localities in NW Spain, where birch trees are more abundant, and between 13% and 60% of individuals who are immunosensitive to pollen grains respond positively to its allergens (Aira et al., 2001; Dopazo, 2001). As a result, models for short-time forecast of airborne birch pollen concentrations were developed in NW Spain and good forecasting results were obtained (Cotos-Yáñez et al., 2004), despite LRT was not included.

In Europe, back-trajectory modelling has been used to identify the arrival of *Betula* pollen from remote sources in Denmark (Mahura et al., 2007; Skjøth et al., 2007), Lithuania (Veriankaite et al., 2010), and United Kingdom (Skjøth et al., 2009, 2015). Additionally, System for Integrated modeLling of Atmospheric coMposition (SILAM) simulations have been applied to trace the origin of LRT of airborne *Betula* pollen in Finland (Sofiev et al., 2006; Siljamo et al., 2008), Russia (Siljamo et al., 2008) and Lithuania (Veriankaite et al., 2010). Recently, the Monitoring of Atmospheric Composition and Climate (MACC, http://www.gmes-atmosphere.eu) regional multi-model simulations of *Betula* pollen dispersion in Europe (Sofiev et al., 2015) also showed that the models successfully reproduced the timing of the pollen season. However, absolute pollen concentrations during the season were underestimated in the southern part of the birch habitat (Sofiev et al., 2015).

Atmospheric back-trajectories and transport models have been profusely used to infer potential sources at receptor locations and identifying the physical location of their origin (Stohl, 1996; Begum et al., 2005; Fleming et al., 2012). Several statistical trajectory based approaches are used in source-receptor studies to identify probable emission sources by combining the trajectories with measured concentrations. For the interpretation of source areas of pollutants, the potential source contribution function (PSCF) (Ashbaugh, 1983), Seibert's concentration field methodology (Seibert et al., 1994) and Stohl's redistributed model (Stohl, 1996) have been extensively used (Charron et al., 2000; Polissar et al., 2001; Hoh and Hites, 2004; Salvador et al., 2004). Recently, the source-receptor methodologies have also been applied to identifying probable source regions of pollen (Belmonte et al., 2008; Izquierdo et al., 2011; Fernández-Llamazares et al., 2014).

In this study, we explore the possible barrier effect of the Pyrenees on the atmospheric transport of airborne pollen from Europe to N Iberian Peninsula. Aerobiological data recorded in three Spanish stations located in the eastern, central and western areas downwind the Pyrenees in the period 2004–2014 have been used to identify the possible LRT episodes of *Betula* pollen. The region where the pollen was originated has been established by means of trajectory statistical analysis using Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. The spatial resolution of the atmospheric transport models has a direct effect on the quality of the simulations, and in the case of the pollen, this has special relevance in areas with complex orography in which the pollen transport is widely governed by complex flows (Skjøth et al., 2002). The nested mesoscale Weather Research and Forecasting (WRF) model was used for simulating specific episodes at higher resolution. In addition, a source receptor model was applied to the *Betula* pollen records to determine the source regions. The meteorological scenarios that favour this transport were also characterized in order to better understand the influence of LRT in the pollen records downwind from the Pyrenees area.

2. Material and methods

2.1. Pollen record

Daily *Betula* pollen concentrations recorded during the birch flowering season (from 1st March to 31st May) at three pollen-monitoring sites located in N Spain for the period from 2004 to 2014 are featured in this study (Fig. 2): Bellaterra (41°30′N 2°06′E, 245 m above sea level (m a.s.l.), Vielha (42°42′N 0°47′E, 980 m a.s.l.) and Vitoria-Gasteiz (42°21′N 2°06′W, 520 m a.s.l.). Samples were obtained using volumetric suction pollen-spore trap based on the impact principle (Hirst, 1952), the standardized method in European aerobiological networks. Daily average pollen concentrations were calculated following the standardized Spanish method (Galán Soldevilla et al., 2007), consisting in analysing four continuous longitudinal sweeps along the 24 h daily slides. Pollen concentrations were expressed as the number of pollen grains per cubic meter of air (pollen/m^3). The Annual Pollen Index (API) is defined as the sum of the mean daily pollen concentrations over the year.

Bellaterra has been chosen as control-station in order to isolate LRT of *Betula* pollen that arrives to the Iberian Peninsula coming from Europe, since the other two stations are influenced by local/regional pollen sources. Two threshold values were used to select *Betula* pollen outbreaks that reached Bellaterra: (1) daily peak pollen concentrations > 10 pollen/m^3, and (2) pollen sum in the episode > 20 p. The hypothesis of this study is that differences between pollen dynamics in the control-station Bellaterra and the rest of stations could be related to different atmospheric transport patterns. Therefore, *Betula* pollen peak episodes detected at control-station Bellaterra were sorted into two groups in order to identify the different atmospheric transport patterns: (1) simultaneous pollen peaks at the three sampling stations and (2) non-simultaneous peaks, which corresponded to pollen peaks observed exclusively at the control-station.

2.2. Meteorological modelling

2.2.1. HYSPLIT back-trajectories

A daily analysis was undertaken based on 96-h isentropic back-trajectories with segment end points of 60-min at 00:00 h and 12:00 h UTC and 1500 m a.s.l. at each sampling station from March to May for the 2004–2014 period by using the HYSPLIT 4.0 dispersion model from the Air Resources Laboratory (ARL, available at http://www.arl.noaa.gov/ready/hysplit4.html, Draxler and Rolph, 2003). This height (1500 m a.s.l.), corresponding to 850 hPa standard pressure level, can be taken as representative of the mean atmospheric transport at a synoptic scale within the upper boundary layer (Izquierdo et al., 2014). This layer is typically sensitive to cyclonic wave features, and is the approximate boundary between the surface wind regime and the free troposphere (Artz et al., 1985). Moreover, a relationship between the 850 hPa wind direction and the prevailing weather patterns associated with the passage of cyclonic waves is well established (Dayan and Lamb, 2003). The meteorological input was obtained from the NCEP (National Center for Environmental Prediction) using the NCEP/NCAR reanalysis database.

The flow direction for the date of the concentration peaks in the *Betula* pollen time series of Bellaterra was analysed with HYSPLIT back-trajectories in the three sampling stations in order to estimate potential source regions and classify the LRT episodes in simultaneous and non-simultaneous pollen peaks.

2.2.2. Meteorological scenarios characterization

In addition to the above procedure, a determination of the meteorological scenarios causing the simultaneous *Betula* pollen outbreaks over the three sampling stations was carried out by means of the analysis of: (1) mean sea level pressure, (2) geopotential height at 850 hPa, and (3) geopotential height at 700 hPa. These are the standard vertical levels commonly used in synoptic scale analysis: 850 hPa corresponding to the 1500 m height of the computed back-trajectories and 700 hPa corresponding to 3000 m. The daily data

Fig. 2. Geographical location of the study area and the aerobiological sampling stations.

files were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF; [accessed September 8, 2015], http://apps.ecmwf.int/datasets/) using the ERA-Interim reanalysis datasets. The synoptic scenarios were obtained from the averaged data of mean sea level pressure and geopotential height of the simultaneous peak days.

2.2.3. Mesoscale modelling

To better understand the atmospheric transport of *Betula* pollen in a region with complex orography such are the Pyrenees, the effects of mesoscale circulation (4–400 km) were incorporated. To this end, version 3.3 of the nested Weather Research and Forecasting (WRF) mesoscale model (Skamarock et al., 2008) was used to simulate, at high resolution, the specific meteorological situations corresponding to two study cases of LRT representative of simultaneous and non-simultaneous pollen episodes: (1) the simultaneous *Betula* pollen peak episode recorded on the 26th of April 2004, and (2) the non-simultaneous peak episode detected on the 27th of April 2006. For these specific situations, back-trajectories were computed at 100, 700 and 1500 m a.s.l from the velocity fields obtained from the WRF simulations. Three nested domains were defined with 18 (D1), 9 (D2) and 3 (D3) km of horizontal grid spacing in both events, having 150 × 150, 220 × 193 and 148 × 148 points, respectively. The simulation in the 2004 case started on the 21th of April 2004 at 00:00 UTC and ran for 162 h; in the case of year 2006 the simulation started on the 22th of April 2006 at 00:00 UTC and lasted for 144 h. In both cases, the boundary conditions were updated every 6 h by using ECMWF operational model data, which also provided the initial conditions. In both simulations, 44 η-levels were used. For the PBL parameterization, we used the MRF scheme (Hong and Pan, 1996), the RRTM scheme for long wave radiation (Mlawer et al., 1997), the Dudhia (1989) scheme for shortwave radiation, and a 6-class radiation (Hong et al., 2004) for the microphysical parameterization. For the land-surface scheme we used Noah model (Chen and Dudhia, 2001), and for surface layer scheme MYJ model (Janjic, 1996a, 1996b). No cumulus parameterizations were used in the smallest domain.

2.3. Source-receptor model

Source-receptor methodologies establish relationships between a receptor point and the probable source areas. To this end, daily HYSPLIT 72-h back-trajectories at 00 and 12 UTM and 1500 m a.s.l. were used. Each back-trajectory was associated to the corresponding daily pollen abundance. Source-receptor methodologies were applied to: (1) the complete set of daily pollen data from the 1st of March to the 30th of May for the 2004–2014 period at the three sampling stations, and (2) the days with simultaneous *Betula* pollen peak. A grid, in our case with 2601 cells of 1° × 1° latitude and longitude, was then superimposed on the integration region of the trajectories in order to map the contributing areas.

A mean pollen concentration is computed for each grid cell based on the residence time of the trajectories in the cells:

$$C_{ij} = \frac{\sum_l n_{ijl} C_l}{\sum_l n_{ijl}}$$

where Cij is the concentration in the cell (i,j), l is the index of the trajectory, n_{ijl} is the number of time steps of the trajectory l in the cell (i,j), and C_l is the pollen concentration measured at the receptor point corresponding to the trajectory l. To reduce the cell's local variability (random noise), a smoothing was applied and the value of each cell was replaced by the average between the cell and its eight neighbouring cells. A final filter excluded cells with < 45 end points, thus producing a more interpretable image. The obtained field map reflects each cell contribution to the pollen concentration at the receptor point.

3. Results

3.1. Birch pollen dynamics in the study area

Betula APIs recorded in the 10-year study period 2004–2014 ranged between 266 and 1832 pollen grains in Vitoria-Gasteiz, 916–3867 in Vielha and 87–487 in Bellaterra (Table 1). The highest mean API was recorded in Vielha with 2186 pollen grains, followed by Vitoria-Gasteiz with 700, and Bellaterra with 179 (Table 1). Temporal trends of *Betula* API observed in the three sampling stations during the 2004–2014 period were non-significant ($p > 0.05$; $R^2 < 0.3$).

3.2. LRT outbreaks of birch pollen from 2004 to 2014

Ten LRT outbreaks of *Betula* pollen were detected from 2004 to 2014. Six of these ten episodes registered *Betula* pollen peak values higher than 30 pollen/m^3 at the control-station Bellaterra, and the rest ranged between 10 and 30 pollen/m^3 (Table 2). Pollen concentrations registered during the pollen peak day at the control-station Bellaterra during the *Betula* pollen outbreaks of pollen detected in the period 2004–2014 ranged between 11 and 146 pollen/m^3 in Bellaterra, 1–135 pollen/m^3 in Vitoria-Gasteiz and 1–293 pollen/m^3 in Vielha. The pollen sum recorded during the LRT episodes varied between 21 and 237 pollen grains in Bellaterra, 39–491 Vitoria-Gasteiz and 7–990 Vielha, which accounted for 18–77% of the API, 7–72% and 0–45% respectively (Table 2).

Analysing the time series there were seven LRT episodes during which peak concentrations of *Betula* pollen were observed simultaneously at the three sampling stations in front of three that exclusively at the control-station Bellaterra (Table 2). Back-trajectories were used to infer the origin of the air masses reaching the stations for these particular days. Fig. 3 shows that back-trajectories of days with simultaneous *Betula* pollen peaks at the three sampling stations, which came from France and Central Europe. However, back-trajectories that arrived at Vitoria-Gasteiz had a more westerly path forming an Atlantic arc over W France, while back-trajectories arriving to Vielha and Bellaterra crossed over the Mediterranean coast of France.

Table 1
Annual Pollen Index (API) registered for *Betula* pollen in the three pollen-monitoring sites for the 10-year period 2004–2014 (pollen grains).

Year	Vitoria-Gasteiz	Vielha	Bellaterra
2004	1332	2324	487
2005	480	2296	87
2006	557	1295	219
2007	619	957	301
2008	553	2169	91
2009	331	1905	177
2010	1832	3442	118
2011	843	916	97
2012	462	2939	90
2013	423	3867	113
2014	266	1942	194
API mean 2004–2014	700	2186	179

Table 2
Daily *Betula* pollen concentrations (pollen/m^3) registered at the three pollen-monitoring stations during the day of the pollen peak of each LRT outbreak at the control-station Bellaterra, the pollen sum registered during these episodes (pollen grains) and the percentage of pollen collected during the episode with respect the Annual Pollen Index (%API). LRT episodes of *Betula* pollen were sorted into two groups: (1) simultaneous pollen peaks registered at the three stations (S) and non-simultaneous peaks (NS).

Betula pollen outbreak dates		Vitoria-Gasteiz			Vielha			Bellaterra (control-station)			
Start	End	Peak	Pollen per episode	% API	Peak	Pollen per episode	% API	Peak	Pollen per episode	% API	S/NS
24/04/04	27/04/04	135	491	37%	225	967	42%	146	237	49%	S
13/05/04	19/05/04	43	132	10%	102	422	18%	41	139	29%	S
12/04/05	14/04/05	25	43	9%	1	7	0%	18	36	41%	S
26/04/06	28/04/06	1	39	7%	2	84	6%	41	77	35%	NS
16/04/07	22/04/07	71	446	72%	37	433	45%	78	154	51%	S
24/04/08	26/04/08	11	81	15%	293	838	39%	21	32	35%	NS
22/04/09	24/04/09	28	109	33%	205	326	17%	41	62	35%	S
10/04/10	11/04/10	103	251	14%	20	127	4%	13	21	18%	S
30/03/12	02/04/12	59	178	39%	8	29	1%	11	23	26%	S
12/04/14	16/04/14	2	83	31%	71	990	51%	39	98	51%	NS

3.3. Meteorological scenarios causing simultaneous birch pollen outbreaks

The meteorological scenario giving rise to the transport of highly *Betula* pollen loaded air masses from France and Central Europe to the Iberian Peninsula is analysed by using sea level pressure maps and contour maps at 850 and 700 hPa for the days with simultaneous peaks. Fig. 4 shows as the driving force causing the transport is due to the presence of a sea level high-pressure system and highs at 700 and 850 hPa over S British Islands reinforced by two lows over Morocco at sea level and at 850 hPa (Fig. 4a, b) and over S Iberian Peninsula at 700 hPa (Fig. 4c). The transport from NE is well detected at the three levels.

3.4. Mesoscale modelling. Study cases

Back-trajectories were also computed with the WRF model in two study cases of LRT of *Betula* pollen: (1) the simultaneous *Betula* pollen peak episode recorded on the 26th of April 2004, and (2) the non-simultaneous peak episode detected on the 27th of April 2006.

3.4.1. Study case 1: simultaneous LRT outbreak of birch pollen on the 26th of April 2004

A significant increase of *Betula* daily airborne pollen concentrations was observed from the 25th to the 27th of April 2004 in the three sampling stations, reaching up to 145 pollen/m^3 in the control-station Bellaterra, 135 pollen/m^3 in Vitoria-Gasteiz and 313 pollen/m^3 in Vielha (Fig. 5). The pollen sum recorded during this outbreak was 237, 491 and 967 pollen grains in Bellaterra, Vitoria-Gasteiz and Vielha, respectively (Table 2), which accounted for 37–49% of the API in 2004 (Table 2).

The synoptic situation during this episode (not shown) was characterized by a high-pressure system centered over Central Europe and low-pressure systems located over the Mediterranean. This resulted in a synoptic circulation with prevailing NE winds from Central Europe to the Iberian Peninsula. The 48-h back-trajectories calculated with WRF model at 100, 700 and 1500 m a.s.l. in D1 from the 24th of April 2004 at 00:00 UTC to the 26th of April 2004 at 00:00 UTC (Fig. 6a–c) showed that air masses approached N Iberian Peninsula after passing over France and central Europe, going around the Alps and Massif Central before they arrived at the Iberian Peninsula. The pathway drawn by 36-h WRF back-trajectory simulations in D3 at the same levels from the 24th of April 2004 at 12:00 UTC to the 26th of April 2004 at 00:00 UTC (Fig. 6d–f) allowed a more refined interpretation of the arrival of pollen to the study area. On the 26th of April 2004, pollen transported by NE air masses were channeled into the lowlands through western and eastern extremities of Pyrenees chain before arriving to Vitoria-Gasteiz and Bellaterra respectively (Fig. 6). Two different pathways were observed in the D3 for the eastern-most air flows before to attain Bellaterra: 1) in parallel to the coast in the Mediterranean Sea at 100 and 700 m a.s.l. (Fig. 6d, e), and 2) through the Alberes region (500 m a.s.l.) at 1500 m a.s.l. (Fig. 6f). Whereas Vielha station was directly impacted by air masses coming from France due to its location on the N side of the Pyrenees, open to France (Fig. 6). Particularly, WRF simulations in D3 showed that air masses travelled through the Garona valley before reaching up Vielha (Fig. 6d–f). A rise of daily *Betula* pollen concentrations was also registered during the previous days at five sampling stations from the French Aerobiology Network (RNSA; [accessed July 1, 2016], http://www.pollens.fr/en/) situated nearby to the pathway drawn by WRF back-trajectory simulations (Fig. 6), being 48 pollen/m^3 in Pau, 49 pollen/m^3 in Toulouse, 240 pollen/m^3 in Perpignan, 384 pollen/m^3 in Aurillac and 225 pollen/m^3 in Strasburg on the 24th of April 2004 (Fig. 5).

3.4.2. Study case 2: non-simultaneous LRT outbreak of birch pollen on the 27th of April 2006

Daily airborne pollen concentrations of *Betula* increased from 2 pollen/m^3 on the 25th of April 2006 to 41 pollen/m^3 on the 27th of April 2006 in the control-station Bellaterra, conversely a significant decrease was observed in the other two sampling stations, where the records resulted ≤ 2 pollen/m^3 on the 27th of April 2006 (Fig. 7). However, the pollen sum registered during this episode was 77 pollen grains in Bellaterra, 88 in Vielha and 39 in Vitoria-Gasteiz, accounting for 35%, 6% and 7% of the 2006 API respectively (Table 2).

The synoptic situation during this episode (not shown) was typified by two high-pressure systems placed over Atlantic at SW of the British Isles and over the S of the Iberian Peninsula, and a low-pressure system over N Italy. According to this synoptic situation, WRF 48 h-back-trajectories at 700 and 1500 m a.s.l. in D1 from the 25th of April 2006 at 00:00 UTC to the 27th of April 2006 at 00:00 UTC (Fig. 8a–c) showed that the air mass flow came from the NW at the three sampling stations. However, back-trajectories at 100 m a.s.l. showed a similar NW influx that passed over the Atlantic before reaching Vitoria-Gasteiz and Vielha on the 27th of April 2006, while air fluxes incoming to Bellaterra came from France. Simulations in D3 showed detailed 36-h WRF back-trajectory at 100, 700 and 1500 m.a.s.l from 25th April 2006 at 12:00 UTC to the 27th of April 2006 at 00:00 UTC (Fig. 8d–f). Atlantic provenance observed in D1 (Fig. 8a–c) at Vitoria-Gasteiz was also observed in D3. However, pathways modelled by WRF in D3 in Vielha came from S France,

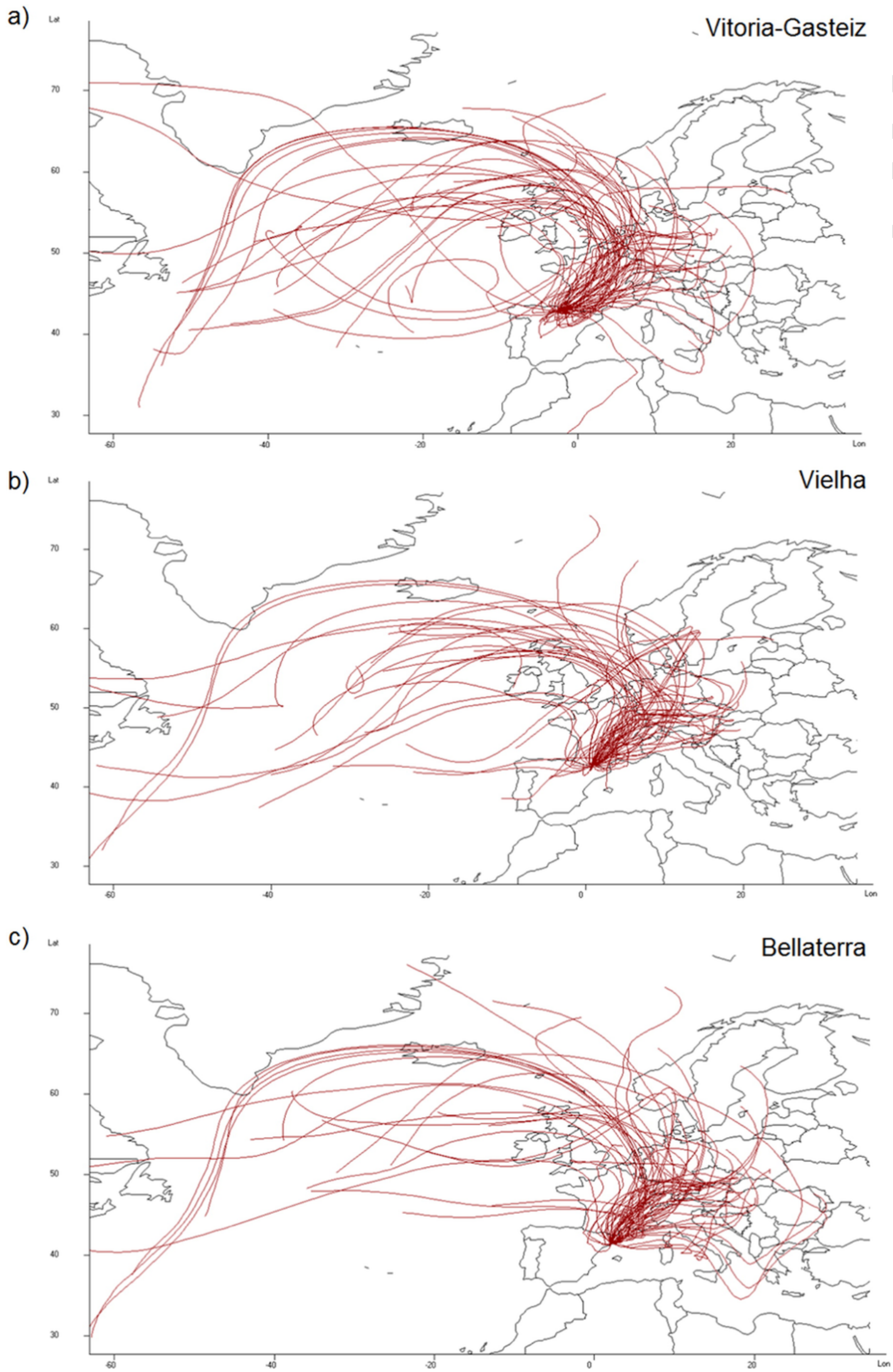
a)
Vitoria-Gasteiz
b)
Vielha
c)
Bellaterra
Lat
Lon

Fig. 3. Daily 96-h HYPSLIT back-trajectories at 00:00 and 12:00 UTC and 1500 m a.s.l. at each sampling station for the days with simultaneous *Betula* pollen peak episodes at the three sampling stations during the period 2004–2014: a) Vitoria-Gasteiz, b) Vielha, and c) Bellaterra.

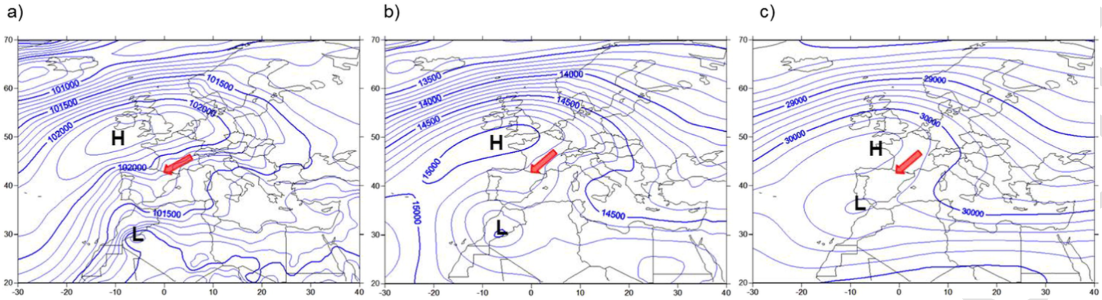

Fig. 4. Meteorological scenarios obtained from the average of daily ERA-Interim data from ECMWF of the simultaneous peak days: (a) mean sea level pressure (hPa), (b) geopotential height at 850 hPa (m), and (c) geopotential height at 700 hPa (m). The red arrows indicate the transport direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

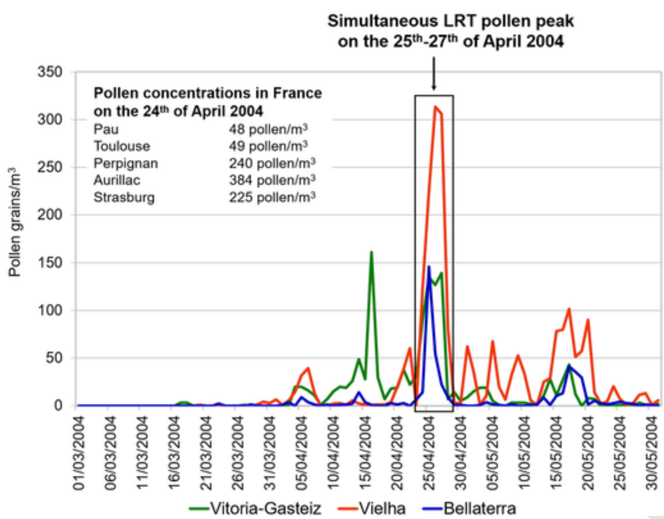

Fig. 5. Mean daily airborne *Betula* pollen concentrations (pollen grains/m^3) registered in: a) Vitoria-Gasteiz, Vielha and Bellaterra from the 1st of March to the 31st of May 2004; b) five sampling stations from the French Aerobiology Network (RNSA; [accessed July 1, 2016], http://www.pollens.fr/en/) on the day previous to the non-simultaneous LRT pollen peak episode. RNSA stations were selected in terms of their location close to the pathway drawn by the WRF back-trajectory simulations that arrived to the study site on the 26th of April 2004.

showing different provenance than in D1, but revealing in the short length and curved shape of their trajectories a more local/regional origin, prevailing over the LRT that would explain the low pollen load. Finally, a consistent flow coming from the region of the French Alps across the Mediterranean coast of France was identified in D1 and D3 at 100 m a.s.l. for Bellaterra (Fig. 8a, d). Conversely, WRF back-trajectories in both domains at 700 and 1500 m a.s.l. were originated in S France and passed through the eastern-most Pyrenean extreme at the Alberes region before reaching up Bellaterra (Fig. 8b–f). Besides, daily Betula pollen concentrations registered on the 26th of April 2006 at five RNSA sampling stations situated nearby to the pathway drawn by the WRF back-trajectory simulations (Fig. 8), showed higher values in Montpellier and Aurillac, accounting for 154 pollen/m^3 and 864 pollen/m^3 respectively, than in Pau, Toulouse and Perpignan, which ranged between 2 and 17 pollen/m^3 (Fig. 7).

3.5. Source-receptor model

Concentration maps of *Betula* pollen derived from the source-receptor model applied to the complete set of daily pollen data from the 1st of March to the 30th of May for 2004–2014 period suggested that France and central Europe were the most likely source areas for the stations placed at extremities of Pyrenees, concretely: N France for Vitoria-Gasteiz (Fig. 9a) and Switzerland for Bellaterra (Fig. 9c). In contrast, distant source-areas were not identified by the source-receptor model in Vielha for this dataset (Fig. 9b) due to the high influence of local sources.

Source-receptor model results obtained for the days with simultaneous *Betula* pollen peak showed that probable source-areas were: (1) SW France for Vitoria-Gasteiz (Fig. 9d); (2) Central and SW France for Vielha (Fig. 9e); and (3) Mediterranean coast of France and Switzerland for Bellaterra (Fig. 9f).

4. Discussion

The high temporal and spatial variability of the *Betula* pollen dynamics observed at the three sampling stations (Table 1) were also noticed in previous studies carried out in NW Spain (Jato et al., 2002; Méndez et al., 2005). These fluctuations have been related to several factors: (1) the location of each sampling station and the spatial distribution **of** *Betula* trees (Fig. 1; De Bolòs et al., 1990; Beck et al., 2016); (2) year-to-year variations of local/regional environmental drivers that control the timing of flowering and the release processes of pollen (Jato et al., 2002); and (3) specific synoptic scale weather systems that affect the phenological stages over a region and also determine the transport of the emitted pollen grains from adjacent and remote regions (Veriankaite et al., 2010). According to these factors, API of *Betula* (Table 1) showed that Vielha was the station that was the most influenced by local sources, followed by Vitoria-Gasteiz. Since contributions of local pollen sources complicated the reliable identification of the long-range episodes, Bellaterra was chosen as control-station as it had the lowest influence of local *Betula* pollen sources.

In accordance with Skjøth et al. (2009), results showed that *Betula* pollen amounts recorded during a single episode represented the 18–77% of the API in the control-station Bellaterra (Table 2), which indicates that *Betula* pollen originated outside of our study area could make a notable contribution to the airborne catch in the three sam-

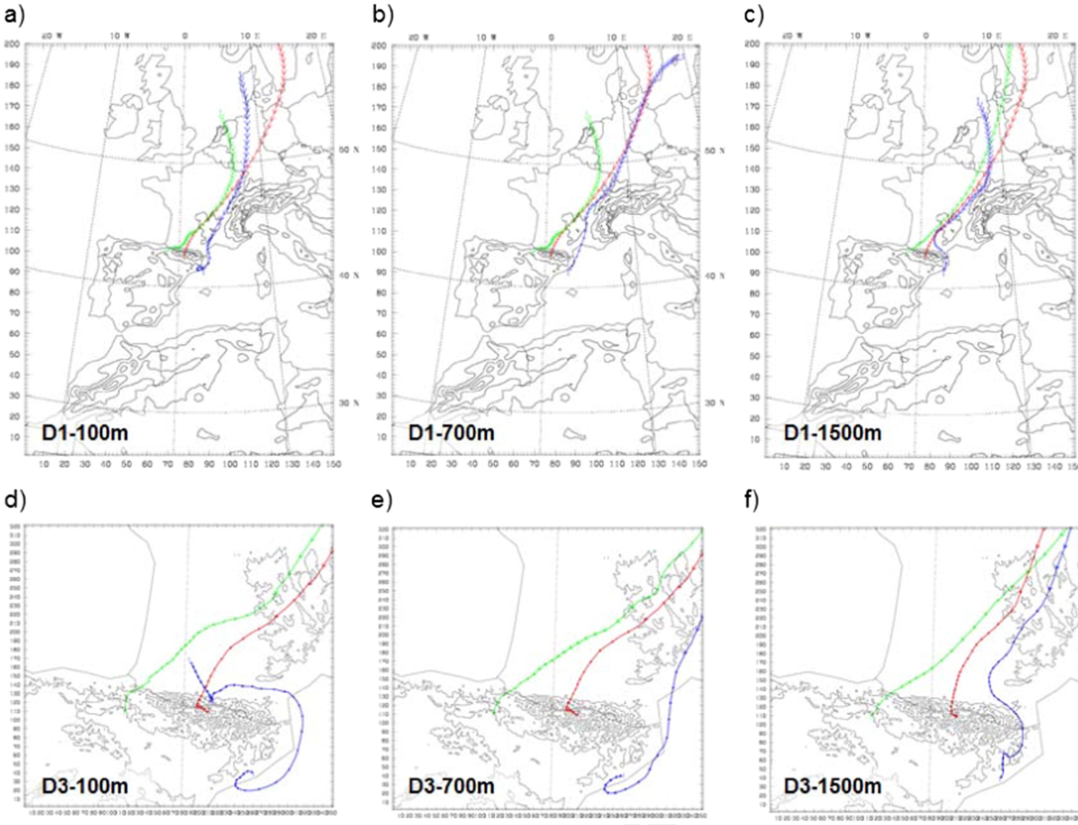

Fig. 6. WRF back-trajectories at 100, 700 and 1500 m a.s.l. arriving on the 26th of April 2004 at 00:00 UTC 48 h length for domain 1 (a, b, c) and 36 h length for domain 3 (d, e, f) at the three sampling stations.

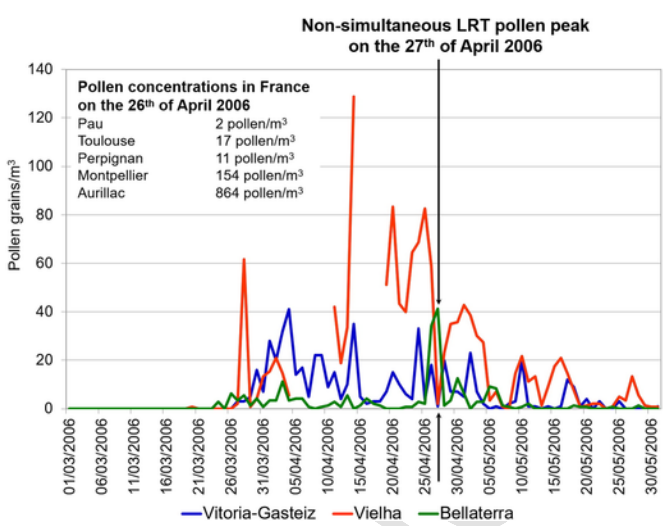

Fig. 7. Mean daily airborne *Betula* pollen concentrations (pollen grains/m^3) registered in: a) Vitoria-Gasteiz, Vielha and Bellaterra from the 1st of March to the 31st of May 2006 (discontinuity in the time serie of Vielha corresponds to missing data); b) five sampling stations from the French Aerobiology Network (RNSA; [accessed July 1, 2016], http://www.pollens.fr/en/) on the day previous to the non-simultaneous LRT pollen peak episode. RNSA stations were selected in terms of their location close to the pathway drawn by the WRF back-trajectory simulations that arrived to the study site on the 27th of April 2006.

pling stations during the main birch pollen season. Seven LRT *Betula* pollen outbreak episodes were registered simultaneously at the three sampling stations and three exclusively at the Bellaterra control-station during the study period. *Betula* pollen values recorded at the control-station Bellaterra during seven of these LRT pollen outbreaks were higher than 30 pollen/m^3, which is the quantity considered sufficient to trigger severe allergy symptoms (Corsico, 1993; Cotos-Yáñez et al., 2004). In the same way, in the study case 1, pollen peaks increased drastically over 80 pollen/m^3, which is the value cited as sufficient to produce symptoms in 90% of the patients (Viander and Koivikko, 1978; Detandt and Nolard, 1996), reaching up to 146 pollen/m^3 in the control-station Bellaterra, 135 pollen/m^3 in Vitoria-Gasteiz and 313 pollen/m^3 in Vielha (Fig. 5). These results brought to light the potential allergenic impact of LRT of *Betula* pollen outbreaks over N Iberian Peninsula, even in Bellaterra where the plant is scarcely present (only for ornamental purposes) and the population with respiratory allergy is not used to being exposed to this pollen. Clinicians should take this pollen type into consideration in certain cases where the etiology of the allergy is not explained by common pollen and spore types.

Back-trajectories have been used to infer the atmospheric pathways of the air masses reaching the stations during these particular days. Previous research showed that even when series of trajectories are used to account for uncertainty, the air masses usually arrive from a relatively confined region (Skjøth et al., 2007). Different atmospheric pathways have been identified during the simultaneous pollen peak episodes. Back-trajectories that arrived at Vitoria-Gasteiz had a westerly path forming an Atlantic arc over W France, while back-trajectories incoming to Vielha and Bellaterra crossed over the Mediterranean coast of France (Fig. 3). The atmospheric routes detected by back-trajectories have been related with the meteorological scenario characterized by the presence of high-pressure systems over S British

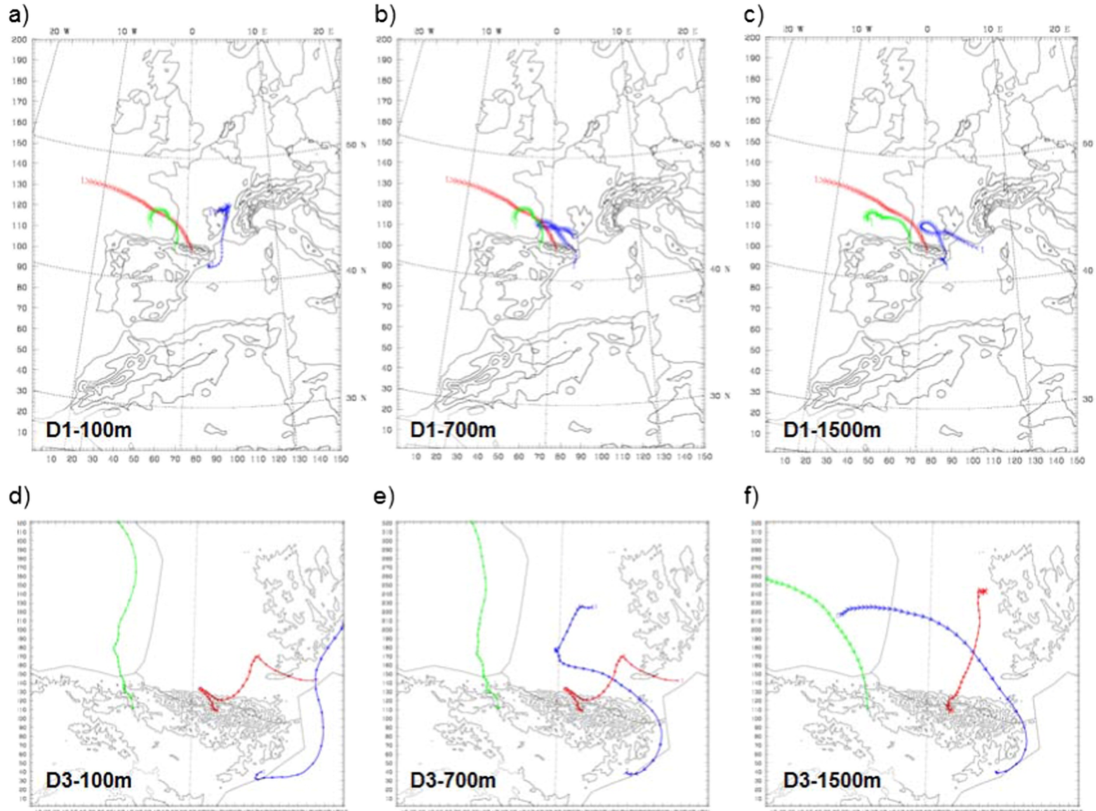

Fig. 8. WRF back-trajectories at 100, 700 and 1500 m a.s.l. arriving on the 27th of April 2006 at 00:00 UTC 48 h length for domain 1 (a, b, c) and 36 h length for domain 3 (d, e, f) at the three sampling stations.

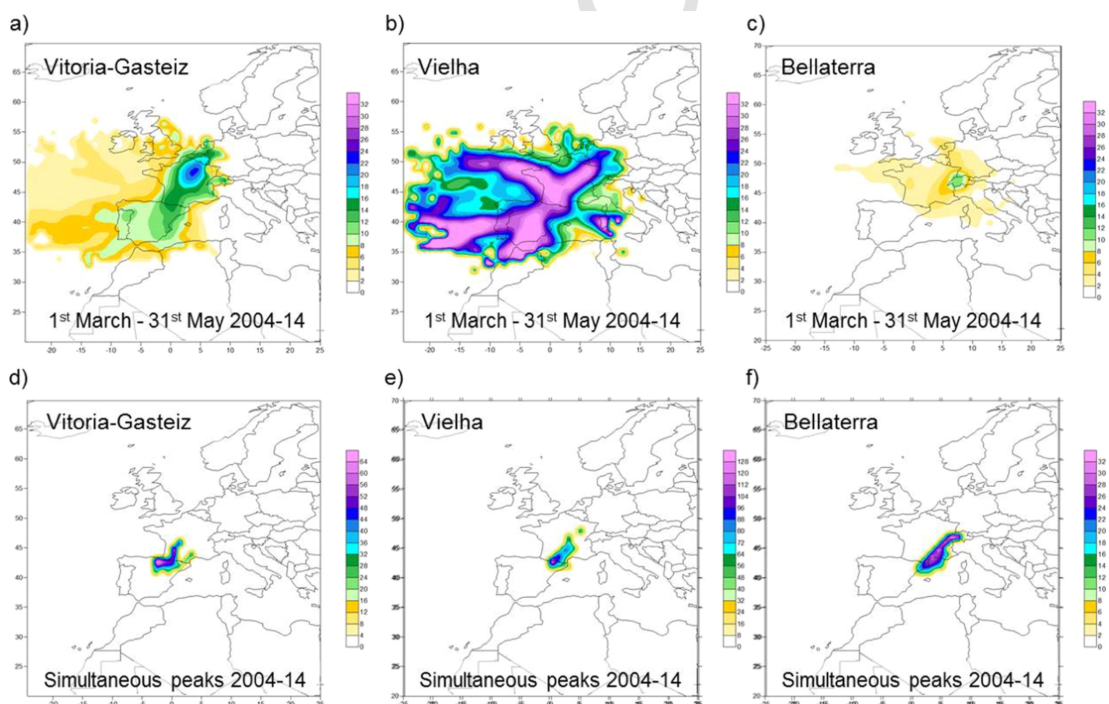

Fig. 9. Concentration maps of *Betula* pollen derived from the source-receptor model. Source-receptor methodologies were applied to: (1) the complete set of daily pollen data from the 1st of March to the 31st of May for the 2004–2014 period (a, b, c); and (2) the days with simultaneous *Betula* pollen peaks in this time series (d, e, f) at Vitoria-Gasteiz, Vielha and Bellaterra. Pollen concentration levels ranged between 0–32 pollen/m^3 in all figures, except in panels d (0–64 pollen/m^3) and e (0–128 pollen/m^3).

Islands at sea level, 850 and 700 hPa reinforced by low-pressure systems over Morocco at sea level and at 850 hPa (Fig. 4a,b) and over S Iberian Peninsula at 700 hPa (Fig. 4c).

Specific episodes modelled by WRF model exhibited the effect of the orography on the atmospheric transport patterns. Specifically, in the simultaneous pollen outbreak registered on the 26th of April 2004 (case study 1, Fig. 5), atmospheric pathways for the three sampling stations were similar in D1, going around the Alps and Massif Central before arriving to the Iberian Peninsula (Fig. 6a–c). However, when air masses coming from France arrived to the Pyrenees, they crossed through western and eastern extremities of the chain to reach Vitoria-Gasteiz and Bellaterra respectively, and impacted directly over Vielha through the Garona *valley* (Fig. 6). These results support the argument that LRT of pollen from Europe to the Iberian Peninsula is a broad-scale phenomenon, being able to cross the Pyrenees when wind is channeled through specific regions, as Les Alberes region and the Garona Valley. This outcome is backed up by increase of *Betula* pollen concentrations observed in the RNSA stations located nearby to the WRF back trajectories pathway in France on the 24th of April (Fig. 5). Both pathways observed in the D3 for the eastern-most air flows before to reaching up Bellaterra are in concordance with the RNSA data. The path through the Mediterranean Sea could be related with the sea breeze influence, which is relevant in the Iberian Mediterranean coastal regions, especially in spring and summer. Besides, the sea breeze is stronger in the Barcelona area, where the Bellaterra station is located, because of the development of the upslope winds on the southern slopes of the coastal mountain range, which contribute to the reinforcement of the general onshore flow (Barros et al., 2003) and the production of *Betula* peaks when these air-masses are pollen loaded. The path through Les Alberes region pass was also traced by the MM5 mesoscale model to describe the LRT transport of *Fagus* pollen from NE France and SW Germany to Catalonia (Belmonte et al., 2008).

Allergenic LRT *Betula* pollen outbreaks could also occur affecting only a particular sampling station, as it has been observed during the non-simultaneous episode registered on the 27th of April 2006 (case study 2, Fig. 7). During this episode, a consistent flow loading *Betula* pollen from France crossed over the easternmost impacting only the control-station Bellaterra (Fig. 8). According with the high pollen concentrations observed on the 26th of April 2006 in Aurillac and Montpellier in front the low values recorded in Toulouse and Perpignan, the most likely pathway for pollen transport was the air flow coming from the region of the French Alps across the Mediterranean coast of France reaching up Bellaterra through the Mediterranean Sea (Fig. 8a, d).

Similarly to the meteorological modelling results, source areas identified by the source-receptor model were located westerly for Vitoria-Gasteiz and displaced through the Mediterranean coast for Bellaterra (Fig. 9). During the main pollen season, France and Central Europe have been established as source areas of *Betula* pollen in Vitoria-Gasteiz and Bellaterra, in particular N France (Fig. 9a) and Switzerland (Fig. 9c), respectively. These results are in accordance with the distribution and abundance of *Betula* trees (Fig. 1), as well as the high mean APIs of *Betula* recorded by RNSA during the 2004–2014 period in the proposed source areas, accounting for 3885 pollen grains in Paris and 3833 in Strasburg. Source-receptor model for the days with simultaneous *Betula* pollen peaks suggested also a west-to-east geographical location of source regions depending on the sampling station, being the probable source areas: the SW France for Vitoria-Gasteiz (Fig. 9d); Central and SE France for Vielha (Fig. 9e), and the Mediterranean coast of France and E Switzerland for Bellaterra (Fig. 9f). The high mean APIs of *Betula* for the 2004–2014 period detected in the RNSA stations of Pau (2304 pollen grains) and Aurillac (5770 pollen grains) support the source areas identified by the source receptor model in SW and Central France. Conversely, the low mean APIs of *Betula* registered during the study period in Perpignan (446 pollen grains) and Montpellier (749 pollen grains) in front to the higher values observed in Grenoble (2296 pollen grains) and Strasburg (3833 pollen grains) point out that E France and E Switzerland were the probable source areas of Betula pollen for Bellaterra. *Betula* forest distribution also supported the hypothesis that discard the Mediterranean coast as source area for Bellaterra.

5. Conclusion

The current study supports the hypothesis that LRT of pollen from Europe and Iberian Peninsula could be a broad-scale phenomenon, being able to cross over the Pyrenees and to produce allergic diseases under specific meteorological situations that favours the atmospheric transport when wind is channeled through regions as Les Alberes and the Garona Valley. Taking into account birch forests distribution and the RNSA pollen records, France and Central Europe have been established as potential source areas of *Betula* pollen that arrives to N Spain, however the specific source areas are mainly determined by the particular prevailing atmospheric circulation of each location. Both meteorological modelling and source-receptor model showed different atmospheric pathways and specific source regions according to the geographical situation of the sampling stations, particularly they came from the west, forming an Atlantic arc over W France, for Vitoria-Gasteiz and moved through the Mediterranean region for Bellaterra. Additionally, WRF model highlighted the effect of the orography on the atmospheric transport patterns, showing paths through the western and easternmost lowlands for Vitoria-Gasteiz and Bellaterra respectively, and the direct impact of airflows on Vielha through the Garona valley. *Betula* pollen outbreaks have been associated to the presence of high-pressure systems located over S British Islands reinforced by low-pressure systems over NW Africa and S Iberian Peninsula. Despite more research is needed to better forecast the timing and severity of these potential allergenic outbreaks, the meteorological scenario identified in this study could be used as first approximation to predict the possible arrival of *Betula* pollen to N Spain during the flowering season with the aim to give advance warning for the allergenic population.

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